REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
10-05-2011	Final Report	25-Aug-2006 - 24-Aug-2010

4. TITLE AND SUBTITLE	
Enabling Technology for Multiple Input Multiple Output (MIMO) Systems on Mobile Military Platforms: Antennas, Switches, and Packaging	5a. CONTRACT NUMBER W911NF-06-1-0366
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611102
6. AUTHORS Jennifer T. Bernhard	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
University of Illinois - Urbana Grants and Contracts Office 109 Coble Hall Champaign, IL 61820 -6242	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO 11. SPONSOR/MONITOR'S REPORT NUMBER(S) 49395-EL.1

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

This project has addressed a number of critical and practical challenges facing the direct integration of RF MEMS switches with reconfigurable antennas. Current designs have been adjusted to account for limitations presented by fabrication techniques available at Georgia Tech. Other antenna designs that require no vias in the layers where the RF MEMS switches reside continue to be developed. We have also demonstrated the real system-level benefits of antenna pattern reconfigurability in MIMO systems through our publications and with collaborations with members

15. SUBJECT TERMS

reconfigurable antenna, RF MEMS switch

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Jennifer Bernhard
UU	UU	UU	UU		19b. TELEPHONE NUMBER 217-333-0293

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

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This project has addressed a number of critical and practical challenges facing the direct integration of RF MEMS switches with reconfigurable antennas. Current designs have been adjusted to account for limitations presented by fabrication techniques available at Georgia Tech. Other antenna designs that require no vias in the layers where the RF MEMS switches reside continue to be developed. We have also demonstrated the real system-level benefits of antenna pattern reconfigurability in MIMO systems through our publications and with collaborations with members of industry (e.g., Intel Corporation).

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. G. H. Huff and J. T. Bernhard, "Integration of packaged RF MEMS switches with radiation pattern reconfigurable square spiral microstrip antennas," IEEE Transactions on Antennas and Propagation, vol 54, no. 2, pp. 464-469, Feb. 2006.
2. J. D. Boerman and J. T. Bernhard, "Performance Study of Pattern Reconfigurable Antennas in MIMO Communications Systems," IEEE Transactions on Antennas and Propagation, vol. 56, no. 1, pp. 231-236, January 2008.
3. T. L Roach and J. T. Bernhard, "Exploration of amplitude tapering in linear phased arrays with pattern reconfigurable elements," Electromagnetics, vol. 29, no. 5, pp. 384-392, July 2009.

Number of Papers published in peer-reviewed journals: 3.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

1. T. L. Roach, G. H. Huff, and J. T. Bernhard, "Enabling High Performance Wireless Communication Systems Using Reconfigurable Antennas," in Proc. Military Communications Conference (MILCOM 2006), Oct. 2006, pp. 1-6.
2. (Invited Special Session Paper) T. L. Roach and J. T. Bernhard, "Investigation of sidelobe level performance in phased arrays with pattern reconfigurable elements," in Proc. 2007 IEEE International Symposium on Antennas and Propagation, Honolulu, HI, June 2007, pp. 105-108.
3. (Invited Special Session Paper) T. L. Roach and J. T. Bernhard, "Exploration of amplitude tapering in phased arrays with pattern reconfigurable elements," in Proc. 2007 International Symposium on Electromagnetic Theory, Ottawa, Canada, July 2007.
4. T. L. Roach, G. H. Huff, and J. T. Bernhard, "On the Applications for a Radiation Reconfigurable Antenna," Proc. Second NASA/ESA Conference on Adaptive Hardware and Systems, August 2007, pp. 7-13.
5. J. Ruyle, C.W. Jung, and J. T. Bernhard, "Reconfigurable Stacked Patch Antenna with Beamsteering Capabilities." Proc. 2008 IEEE International Symposium on Antennas and Propagation, San Diego, CA, July 2008, pp. 1-4.
6. J. E. Ruyle and J. T. Bernhard, "Investigations of a Reconfigurable Stacked Patch with Beamsteering Capabilities," in Proc. 2008 Antenna Applications Symposium, Allerton Park, Monticello, IL, Sept. 2008.
7. T. L. Roach and J. T. Bernhard, "Antenna Element Pattern Reconfigurability in Adaptive Arrays," in Proc. 2008 Antenna Applications Symposium, Allerton Park, Monticello, IL, Sept. 2008.
8. T. Wojtaszek, G. Huff, D. J. Chung, J. Papapolymerou and J. T. Bernhard, "Reconfigurable Antennas with Integrated RF MEMS Switches for Military MIMO Applications," in Proc. URSI 2009 National Radio Science Meeting, January 2009.
9. T. Wojtaszek, J. T. Bernhard, G. H. Huff, D. J. Chung, and J. Papapolymerou, "Reconfigurable Antennas with Integrated RF MEMS Switches for Military MIMO Applications," in Proc. GOMAC TECH 2009, March 2009.

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 9

(d) Manuscripts

Number of Manuscripts: 0.00

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
Thomas Wojtaszek	1.00
Joshua Boerman	0.50
Tyrone Roach	0.50
FTE Equivalent:	**2.00**
Total Number:	**3**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Jennifer T. Bernhard	0.10	No
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
Thomas Wojtaszek	
Joshua Boerman	
Total Number:	**2**

Names of personnel receiving PHDs

NAME	
Tyrone Roach	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attached.

Technology Transfer

Enabling Technology for Multiple Input Multiple Output (MIMO) Systems on Mobile Military Platforms: Antennas, Switches, and Packaging

Final Report

August 25, 2006 – August 31, 2010

by

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US Army Research Office
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Under Grant No. 49395-EL

Introduction

A number of groups have suggested antennas for use in MIMO systems, including monopoles, dipoles, spiral antennas, biconical antennas, and “cube antennas” constructed of multiple dipoles. Unfortunately, all of these face two major problems. First, none of these designs can be easily integrated into different portable devices as antennas for wireless local area networks (WLAN), Bluetooth, etc. are in today’s commercial products. As practical MIMO systems are deployed, consumers will continue to expect “hidden, worry-free” antennas. Second, they each have fixed behaviors so that they cannot respond to changing propagation channels. Other have used arrays of planar elements to evaluate MIMO channels, but, again, these large structures, when integrated into a portable device, will not be able to fully exploit rich multipath environments since they point in one fixed direction.

Antenna reconfigurability provides the ability to change fundamental operating characteristics through electrical, mechanical, or other means. A number of research groups have pursued frequency reconfigurability in the context of large defense-based apertures. However, for most portable wireless communications systems, well-know multi-band designs can serve this purpose easily. The PI (Prof. Bernhard) and her group in the Electromagnetics Laboratory at the University of Illinois with prior support from NSF developed prototype, single microstrip antenna elements with the capability to ***change the direction, beamwidth, and polarization of their radiation patterns through switched connections while maintaining their operating frequency.*** A picture of one of these prototypes is shown in Fig. 1. To date, two versions of the antenna have been demonstrated: (1) one with capabilities to switch between a broadside beam and a beam with a 45^0 tilt from broadside and (2) one with capabilities to switch between a broadside beam and an endfire beam (measurements shown in Fig. 2). While each of these designs has two switched connections, other antennas can be designed with more switches and more operational states. To date, both solid state switches and pre-packaged commercial RF MEMS switches have been implemented in these antennas, but ultimately, both approaches restrict the possible current distributions that the antenna can support because of package size, parasitics, and complicated bias networks.

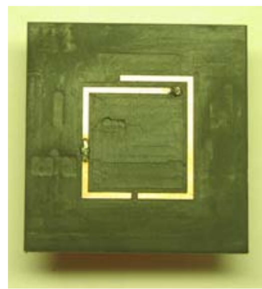


Fig. 1: Pattern reconfigurable antenna. Depending upon switch location, patterns can range from broadside to endfire with linear polarized beams.

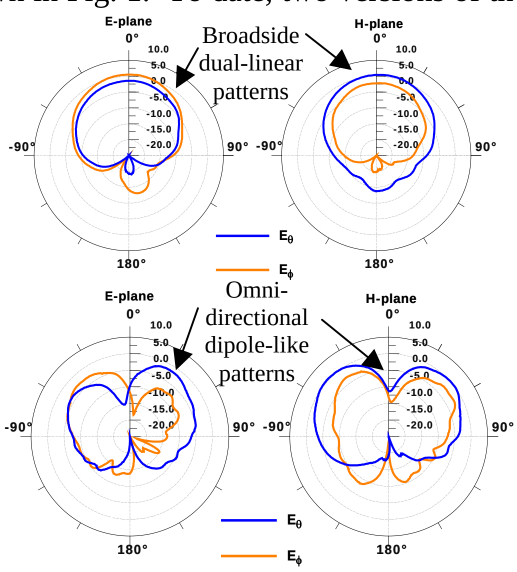


Fig. 2: Measured radiation patterns from a single reconfigurable antenna operating at 6.9 GHz. Switch connections were hard-wired for proof of concept.

Major Activities and Findings

Our previous work in the development of pattern reconfigurable antennas, as well as that of others pursuing reconfigurable apertures, has proven that trying to mate an antenna design with an *off-the-shelf, general purpose* RF MEMS switch will not work well. Likewise, generic implementation of common antennas in traditional positions on portable MIMO devices will not deliver the promised capacity because coupling caused by induced chassis currents will increase channel correlation. Through this work, *we successfully developed a family of* ***radiation pattern reconfigurable antennas equipped with RF MEMS switches designed specifically for these applications***. Moreover, we have leveraged our expertise in this area and demonstrated the ***system-level benefits of pattern reconfigurability*** in such systems. The following sections detail our progress over the final year of the grant.

Pattern Reconfigurable Antenna Development

Square Spiral Design

With the help of the team from Georgia Tech, we have fabricated a design for an integrated pattern reconfigurable antenna with integrated RF MEMS switches. The fabrication process took much longer than expected, owing to unavoidable equipment limitations at Georgia Tech. The basic antenna design is shown in Figure 3. In the endfire configuration, the switch location at c' is closed and the switch location at e' is open. In doing so, the single turn square Archimedean spiral geometry is recovered. In the broadside configuration, the switch location at c' is open and the switch location at e' is closed.

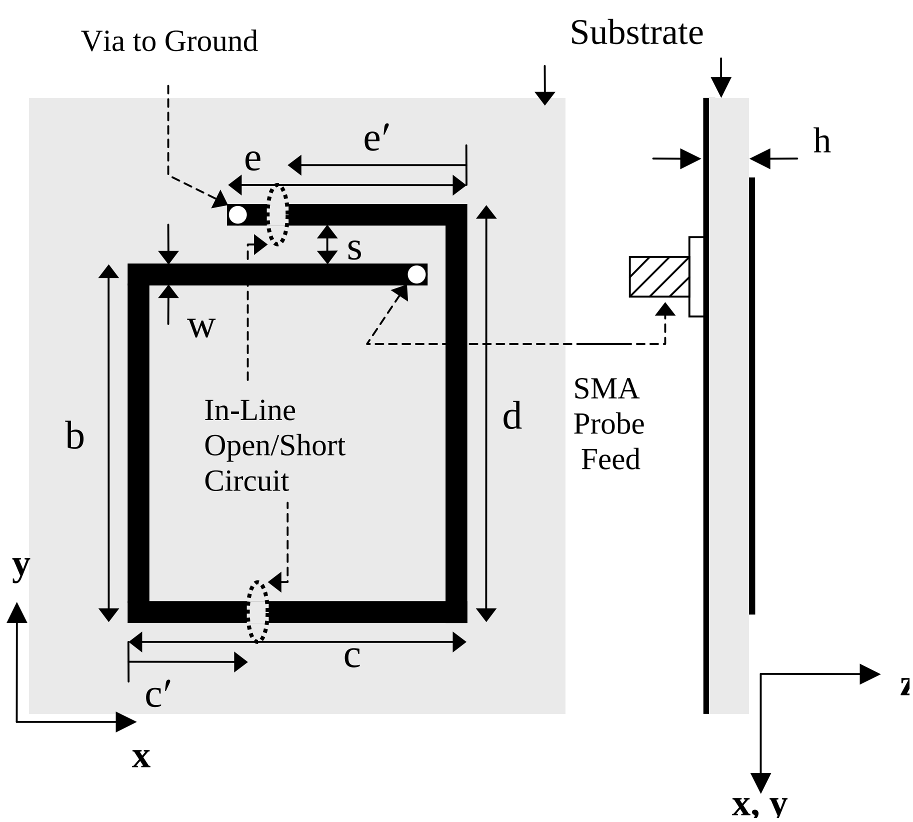


Figure 3: Basic antenna geometry including switch locations.

The biggest challenge thus far has been the design of the antenna within the constraints set by the fabrication process. In particular, shapes and dimensions for vias can dramatically affect the antenna's impedance and radiation behavior. The selected substrate is liquid crystal polymer (LCP), which has a relative permittivity of about 3.15. We began our work with a Ka-band design at 27.5 GHz. The details of the via structure and design are shown in Figure 4.

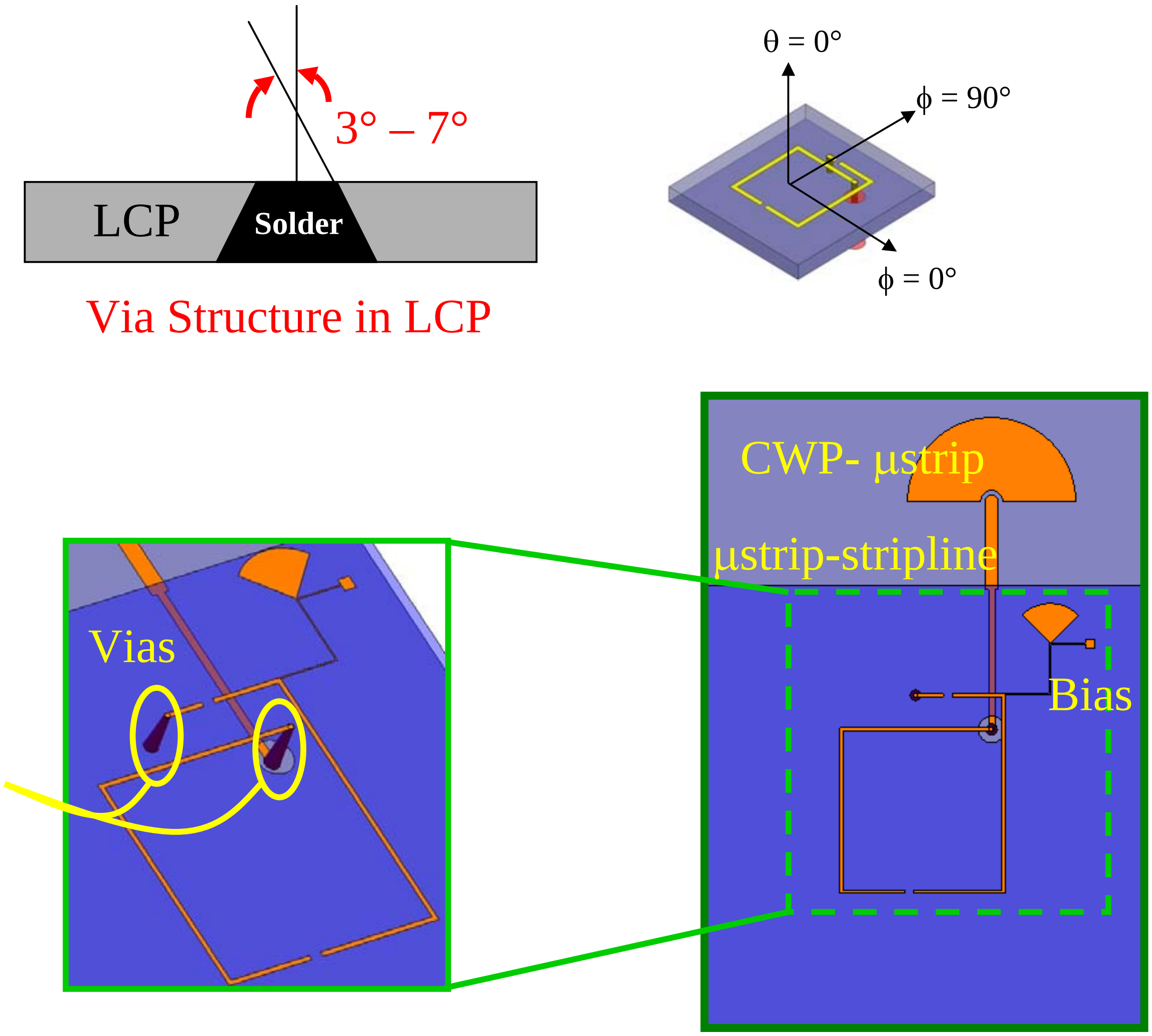


Figure 4: Details of designed via structure and antenna layout.

Simulations of this design using HFSS show that the radiation pattern reconfiguration is preserved with this complicated structure and with the vias as designed. This design was fabricated at Georgia Tech and is shown in Figure 5 showing holes drilled by hand at Illinois. To enable the antenna feeds and required vias, we inserted small, custom coaxial cables with suitable connectors to enable reliable testing of these antennas.

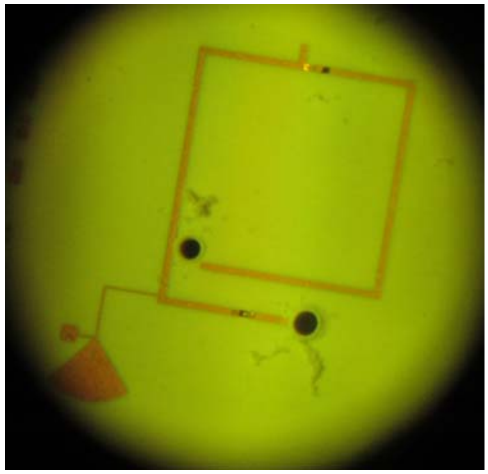


Figure 5: Photograph of fabricated reconfigurable antennas for operation around 26 GHz showing drilled holes for feed and grounding pin connections.

The reconfigurable square spiral microstrip antenna configured for 26 GHz, part of the Ka frequency band, underwent testing. In order to test the antennas we had to obtain special cables that mate well with the tiny features of the traces. In particular, Storm Products Company [1] made a special cable with center conductor diameter of 0.047 inch with a GPPO end adapter. The center conductor acts as the excitation pin, analogous to an SMA probe, and the outer shielding was used as the ground plane connection. To ensure a good connection and to keep the center conductor in place a conductive adhesive needed to be used. Compound Silver 402 [2], a silver-filled epoxy adhesive, by Resin Technology Group was chosen because of its easy curing procedure. Once applied to the antenna/conductor junction the curing schedule called for 18 hours at 25°C (room temperature) [2]. This made combining the antenna substrate and cabling simple since it did not require any heating to cure the epoxy. For initial measurements due to fabrication yield issues, the switches were hard-wired using the same silver epoxy. For end-fire operation, switch c' was closed while switch e' was left open.

To ensure there is a good connection between the center conductor and traces as well as a match at the desired frequencies, the antenna input impedance was tested. The tests confirmed the good connection as well a good match, although not exactly at 25.8 GHz rather than 26 GHz.

<u>*Compound Reconfigurable Antenna Development*</u>

Reconfigurable Ring Resonator

In order to decrease the package size of antennas, multiple applications need to be integrated together in one structure. One way to combine applications is to create a single antenna that can be both frequency- and pattern-reconfigurable, which we term "compound reconfigurable." This section describes the development of such an antenna undertaken under this grant. The antenna provides broadside and endfire radiation at frequencies of 1.38 GHz and 2 GHz.

The ring resonator antenna design is based on the resonance characteristic of a microstrip ring. A pattern-reconfigurable design using this layout was presented by Chen et al. in [6]. It is based on their previous designs of a dual frequency [7, 8] and wideband monopolar square-ring patch antenna [9-11]. Their design works on the principle of exciting the TM_{11} resonant mode of a microstrip ring for broadside pattern operation [12-14] and shorting those same rings to the ground plane for a loaded monopolar endfire pattern [9-11]. The work here takes these designs and incorporates them into a single structure for both frequency- and pattern-reconfigurable operation. The base geometry consists of these microstrip ring resonators fed through capacitive coupling by a patch in the center. Varying the size of the patch and its separation from the ring, this feeding structure can provide enhanced impedance bandwidth [15, 16]. These methods, along with several others, are used in this research to develop the compound reconfigurability at 1.4 and 2.0 GHz, making the antenna as efficient as possible within the constraints.

Figure 6 shows the geometry of the dual square ring configuration. There is a 0.03 in (0.767 mm) thick substrate, labeled *diel_h*, used to support the traces above the ground plane. Labeled as *sub_h*, the total space between the ground and traces is 7 mm.

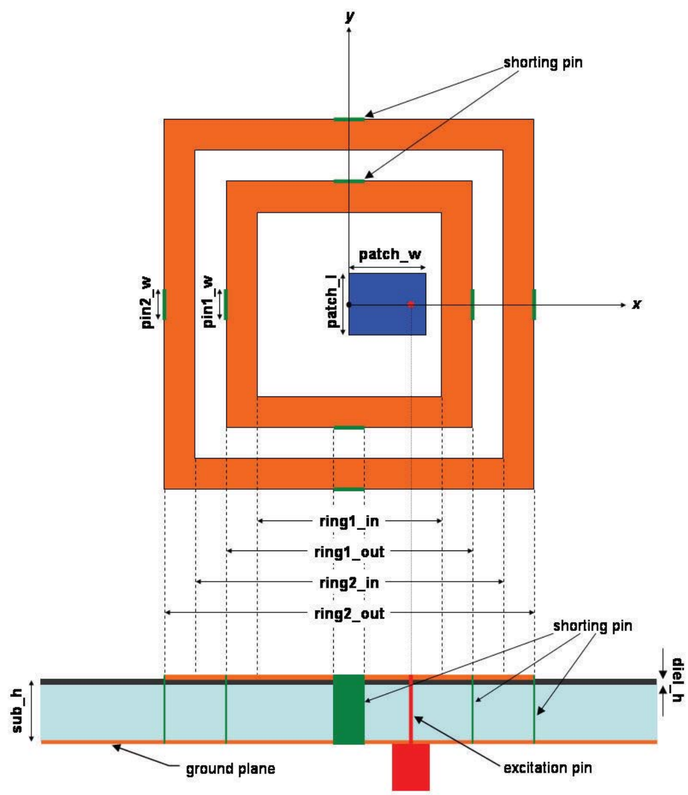


Figure 6: Ring resonator geometry for the compound reconfigurable antenna.

The substrate is a Rogers 4003C dielectric with relative permittivity of 3.55. The inner ring has a width of 5 mm, determined by *ring1_in* and *ring1_out* being 28 mm and 38 mm, respectively. *Ring2_in* is 45 mm while *ring2_out* is 55 mm, making the width 5 mm. The average ring radius, for example (*ring1_in* + *ring1_out*)/2, determines the length used in wavelength calculations; they are 33 mm and 50 mm for the inside and outside modes, respectively. In Figure 6, shorting pins *pin1_w* and *pin2_w* are both 0.5 mm in width and are shown in green. Shown in Figure 7 is a magnified view of the coupling patch, which is one of the keys to creating the multifunctional behavior of the antenna.

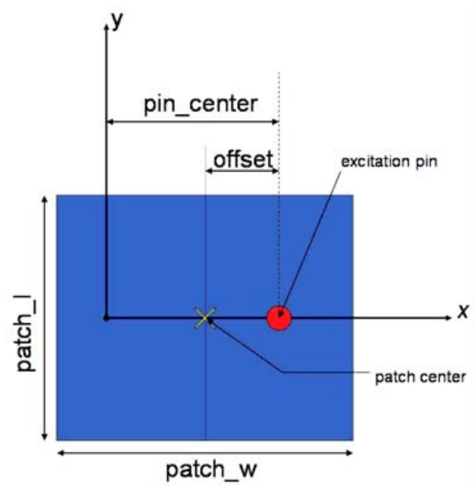
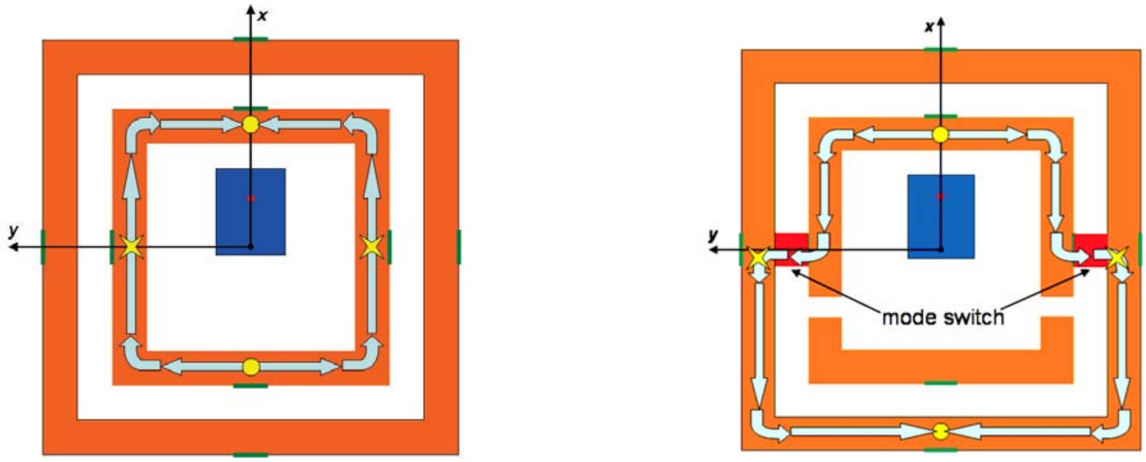


Figure 7: Magnified view of coupling patch.

The size of the patch will be written as "*patch_w* by *patch*_l." The excitation probe and the center of the patch, shown as a yellow star, are always located on the x-axis, while pin center is the probe distance from the y-axis. For several of the matching methods presented later, the probe is offset from the center of the patch which is labeled as offset. The center of the patch is moved in the negative x-direction when offset is negative and vice versa.

Figure 8 presents the expected current distribution for the TM_{11} modes. Because the total length of the ring is a full wavelength, a sine wave represents the distribution with two magnitude nulls, shown as circles, and two magnitude maximums, shown as stars. This current distribution creates a broadside radiation pattern, since the electric field between the traces and ground mimics that of a simple patch antenna. The TM_{11} mode of the ring resonators is meant to radiate as a patch antenna but with a smaller overall conductor footprint. This current distribution is disturbed to create an endfire mode by shorting the pins to the ground, making the current travel down to ground. This creates an array of loaded monopoles and, as will be presented in the simulation and measurement section, the radiation patterns have a E_θ polarization since the current is oriented in the vertical direction, parallel to the z-axis. Although current still has to travel along the rings to reach the pins, the distribution is such that it creates no far-field patterns. Because the outer ring is too far away from the coupling patch, the inner ring is shorted to the outer ring to provide direct coupling and a path for the current to travel. The switch is placed on the y-axis as shown by the short, red in the color version, in Figure 8(b). Although this solves the coupling problem, it creates a problem in that the inner ring still radiates because of the current distribution still present. To remedy this, the inner ring is cut right below the switch as shown in Figure 8(b). The cut destroys the TM_{11} current distribution and with it the impedance match and radiation conditions for the inner modes. The outside monopole mode works exactly as the inner monopole mode. The outer ring is shorted to the ground, and the vertical current on the pin creates an E_θ polarized endfire pattern.



(a) Inside TM_{11} Mode **(b) Outside TM_{11} Mode**

Figure 8: Current distribution for TM_{11} modes.

Several different methods were tested in an attempt to get all four modes working correctly. Correct operation consists of not only getting a match at the center frequency but also radiating the appropriate pattern. In the final design, a feed patch shape is selected that integrates both the wide and the narrow patch by using switches to connect two outer panels to the main part when the inner modes are operating. Although not perfect, this geometry does a good job of creating a match for all four modes, but the drawback is added complexity. Acceptable broadside patterns with a realized gain of 8.66 dB for E_θ and 8.55 dB for E_φ are achieved in simulation using this configuration for the inside TM_{11} mode. In the inside monopole mode, simulation shows good endfire patterns with realized E_θ gain of 3.75 dB in the $\varphi = 0°$ plane and 3.09 dB in the $\varphi = 90°$ plane. Detailed measured results can be found in [17].

Performance Benefits of Pattern Reconfigurability in MIMO Systems

Another aspect of this project is the analysis of the use of reconfigurable antennas in MIMO systems. We published a journal article based on an M.S. thesis (by graduate student J. D. Boerman) that details the possible performance benefits of beam-tilted antennas in these systems [4]. The results show that the optimally configured reconfigurable antennas significantly improve the capacity of the system versus similar non-reconfigurable antennas and versus isotropic antennas.

In addition to the two-antenna MIMO configurations already studied, we added a new structure for study that has a corner cube topology. A simulation prototype (implemented using simple microstrip patch antenna elements for the time being) is shown in Figure 9. In the future, we plan to implement radiation pattern reconfigurable antennas in this topology to provide additional spatial diversity and coverage for mobile applications.

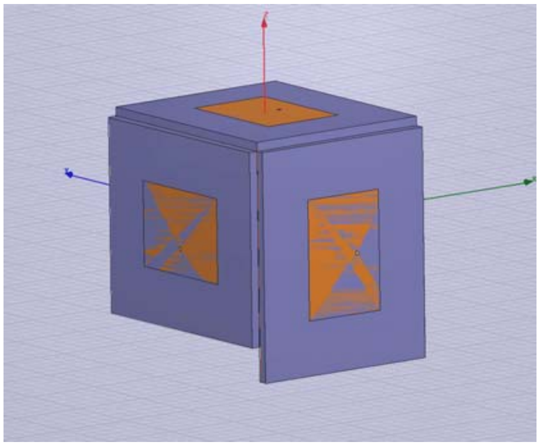


Figure 9: Three element MIMO antenna array in a cubic configuration.

Discussion and Future Work

The experience acquired over the course of this project leads to the significant finding that fabrication of antennas and RF MEMS switches together on the same substrate is possible and feasible. However, in order for such designs to have widespread adoption for MIMO systems, fabrication of the required vias for antenna feeding and control lines must also advance so that vias can be easily and reliably made in substrate thicknesses on the order of mm. To surmount this current limitation, we continue to develop new reconfigurable microstrip antenna designs that eliminate the need for any vias in layers where RF MEMS switches reside.

This work has also examined and analyzed the potential improvements in MIMO system capacity attainable through use of a small number of pattern reconfigurable antennas. The simulation and experimental results in various multipath propagation scenarios indicates that large performance enhancements are possible compared to systems that use either fixed or randomly directed pattern reconfigurable antennas. These benefits are particularly significant when the antenna patterns can be directed optimally to not only possess a high degree of diversity but also to provide enhanced SNR through increased antenna gain.

Future work in this area includes the quantitative evaluation of reconfigurable antennas in other scientifically reproducible environments. These experiments, conducted in both real and simulated scenarios, will also be used to determine what kind of antenna pattern reconfigurability will be most advantageous and responsive in these environments, leading to the development of new kinds of reconfigurable antennas. Additionally, for all of these cases, an overall system performance analysis could be conducted that includes the effects of receiver noise as in [5]. Finally, work will continue on the design and integration of appropriate control algorithms for reconfigurable antennas that will use system-level performance measures as inputs.

References

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[17] T. Wojtaszek, *Reconfigurable Antennas for Multiple-Input Multiple-Output Applications*, M.S. Thesis, University of Illinois at Urbana-Champaign, August 2009.

Education Activities and Opportunities for Training and Development

Since the beginning of this project, seven graduate students have performed research and training activities related to the goals of this project. One of them was funded directly through this grant, with funding for the others coming from external fellowships, teaching assistantships, etc. Results of this research have also been integrated into ECE 457: Microwave Circuit Design and

ECE 454: Antennas, both senior/graduate-level courses in the ECE Department at the University of Illinois at Urbana-Champaign.

Contributions

This project has addressed a number of critical and practical challenges facing the direct integration of RF MEMS switches with reconfigurable antennas. Current designs have been adjusted to account for limitations presented by fabrication techniques available at Georgia Tech. Other antenna designs that require no vias in the layers where the RF MEMS switches reside continue to be developed. We have also demonstrated the real system-level benefits of antenna pattern reconfigurability in MIMO systems through our publications and with collaborations with members of industry (e.g., Intel Corporation).

Products

Conference papers, journal papers, and related graduate theses supported by this grant

1. G. H. Huff and J. T. Bernhard, "Integration of packaged RF MEMS switches with radiation pattern reconfigurable square spiral microstrip antennas," *IEEE Transactions on Antennas and Propagation*, vol 54, no. 2, pp. 464-469, Feb. 2006.
2. T. L. Roach, G. H. Huff, and J. T. Bernhard, "Enabling High Performance Wireless Communication Systems Using Reconfigurable Antennas," in *Proc. Military Communications Conference (MILCOM 2006)*, Oct. 2006, pp. 1-6.
3. J. D. Boerman, *Performance Study of Pattern Reconfigurable Antennas in Multiple-Input Multiple-Output Communications Systems*, M.S. Thesis, University of Illinois at Urbana-Champaign, May 2007.
4. (Invited Special Session Paper) T. L. Roach and J. T. Bernhard, "Investigation of sidelobe level performance in phased arrays with pattern reconfigurable elements," in *Proc. 2007 IEEE International Symposium on Antennas and Propagation*, Honolulu, HI, June 2007, pp. 105-108.
5. (Invited Special Session Paper) T. L. Roach and J. T. Bernhard, "Exploration of amplitude tapering in phased arrays with pattern reconfigurable elements," in *Proc. 2007 International Symposium on Electromagnetic Theory*, Ottawa, Canada, July 2007.
6. T. L. Roach, G. H. Huff, and J. T. Bernhard, "On the Applications for a Radiation Reconfigurable Antenna," *Proc. Second NASA/ESA Conference on Adaptive Hardware and Systems*, August 2007, pp. 7-13.
7. J. D. Boerman and J. T. Bernhard, "Performance Study of Pattern Reconfigurable Antennas in MIMO Communications Systems," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 1, pp. 231-236, January 2008.
8. J. Ruyle, C.W. Jung, and J. T. Bernhard, "Reconfigurable Stacked Patch Antenna with Beamsteering Capabilities." *Proc. 2008 IEEE International Symposium on Antennas and Propagation*, San Diego, CA, July 2008, pp. 1-4.
9. J. E. Ruyle and J. T. Bernhard, "Investigations of a Reconfigurable Stacked Patch with Beamsteering Capabilities," in *Proc. 2008 Antenna Applications Symposium*, Allerton Park, Monticello, IL, Sept. 2008.

10. T. L. Roach and J. T. Bernhard, “Antenna Element Pattern Reconfigurability in Adaptive Arrays,” in *Proc. 2008 Antenna Applications Symposium*, Allerton Park, Monticello, IL, Sept. 2008.
11. T. Wojtaszek, G. Huff, D. J. Chung, J. Papapolymerou and J. T. Bernhard, “Reconfigurable Antennas with Integrated RF MEMS Switches for Military MIMO Applications,” in *Proc. URSI 2009 National Radio Science Meeting*, January 2009.
12. T. Wojtaszek, J. T. Bernhard, G. H. Huff, D. J. Chung, and J. Papapolymerou, “Reconfigurable Antennas with Integrated RF MEMS Switches for Military MIMO Applications,” in *Proc. GOMAC TECH 2009*, March 2009.
13. T. L Roach and J. T. Bernhard, “Exploration of amplitude tapering in linear phased arrays with pattern reconfigurable elements,” *Electromagnetics*, vol. 29, no. 5, pp. 384-392, July 2009.
14. T. Wojtaszek, *Reconfigurable Antennas for Multiple-Input Multiple-Output Applications*, M.S. Thesis, University of Illinois at Urbana-Champaign, August 2009.

Job placements for graduate students involved in this work:

- Joshua D. Boerman, M.S.: Currently technical staff at Motorola Corporation, Libertyville, IL.
- Gregory H. Huff, Ph.D.: Currently Assistant Professor in the ECE Department at Texas A&M University. NSF CAREER and ARO PECASE Award Winner.
- Tyrone L. Roach, Ph.D., Currently member of technical staff, Georgia Tech Research Institute
- Jessica E. Ruyle, M.S. and current Ph.D. student, University of Illinois at Urbana-Champaign.
- Nicholas Soldner, M.S., Currently technical staff at United Technologies Research Center, Stratford, CT.
- Tomasz Z. Wojtaszek, M.S.: Currently technical staff at US SPAWAR, San Diego, CA.
- Shenghui Zhang, Ph.D., Currently technical staff at Chinese Heng-Xing Inc., Beijing, China.